PFA electromagnetic calorimetry prototypes: R&D Status and Highlights

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on behalf of the CALICE Collaboration

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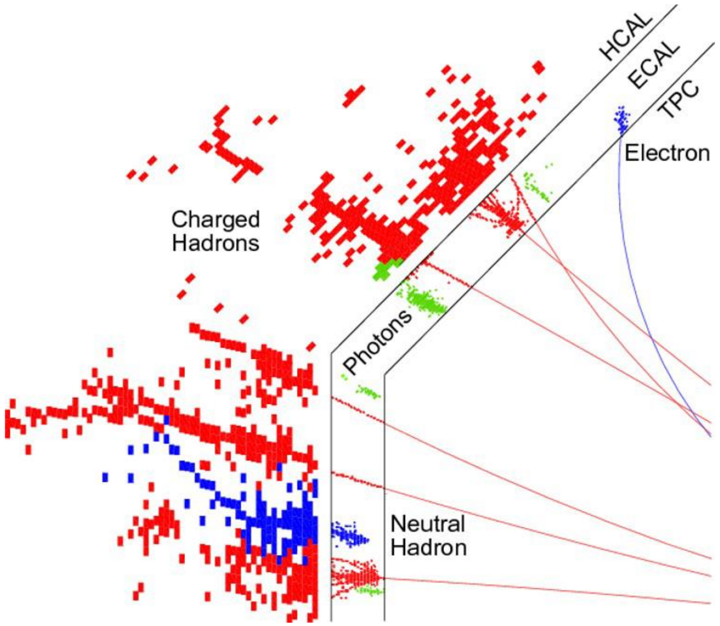
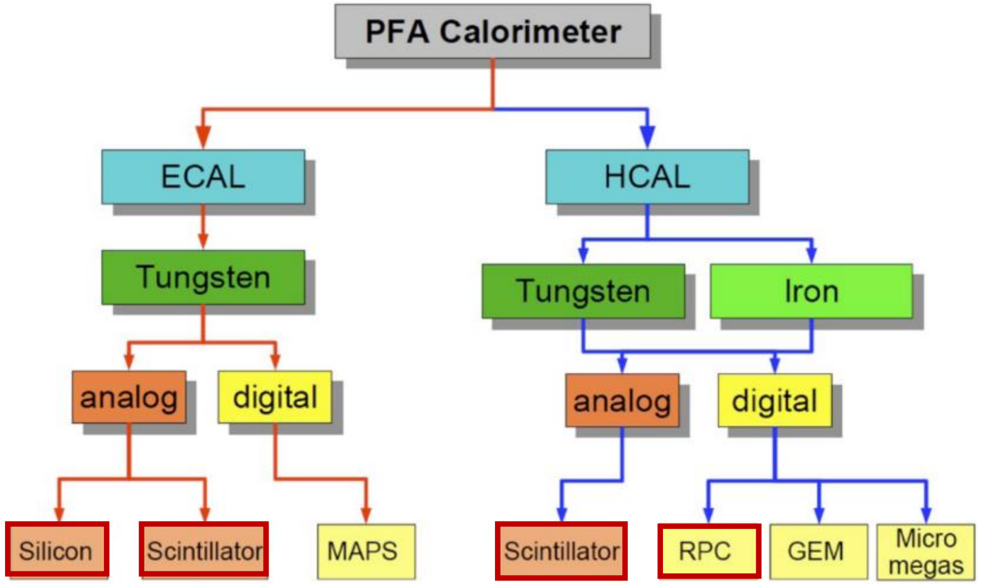
2021 international workshop on the high energy Circular Electron-Positron Collider (CEPC)

Introduction: Particle Flow Detectors

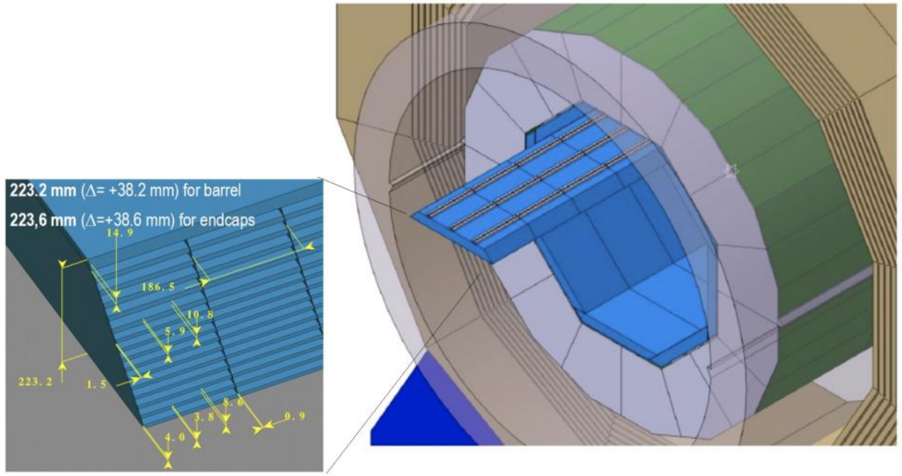
- Particle flow paradigm: for precision measurement of jets
  - Measurements of individual particles
  - Maximal exploitation of precise tracking
- General concepts
  - Choose sub-detector best suited for each particle type
  - Separate showers of close-by particles in the calorimeters
    - Need to minimize the confusion term
- High-granularity (imaging) calorimeters: PFA-oriented
  - Emphasis on tracking capabilities of calorimeters
  - Hardware: readout channels on the order of 1~10 million
  - Compact: all calorimeters inside magnet coil
  - Hermetic: minimum gaps
  - Limited space for instrumentation

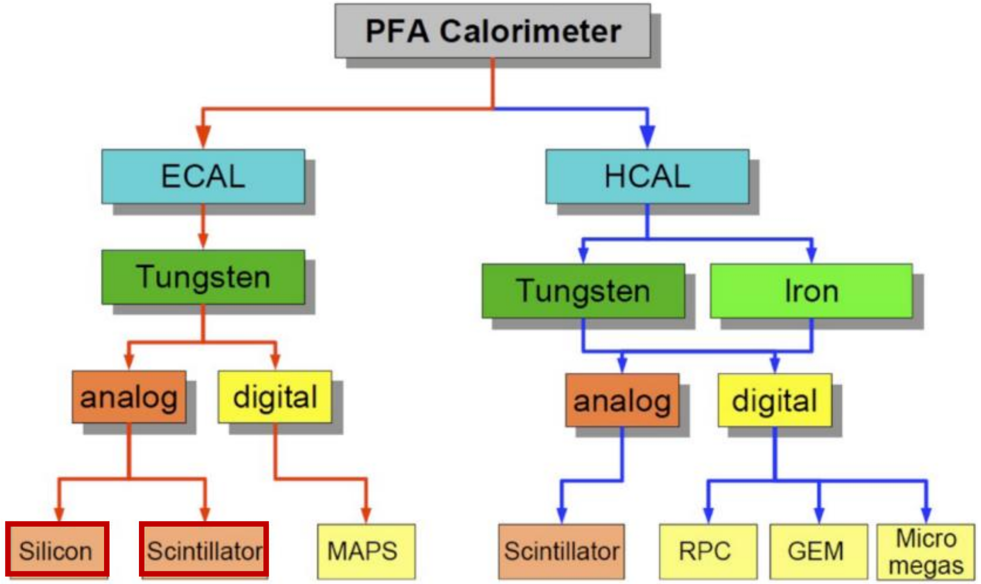




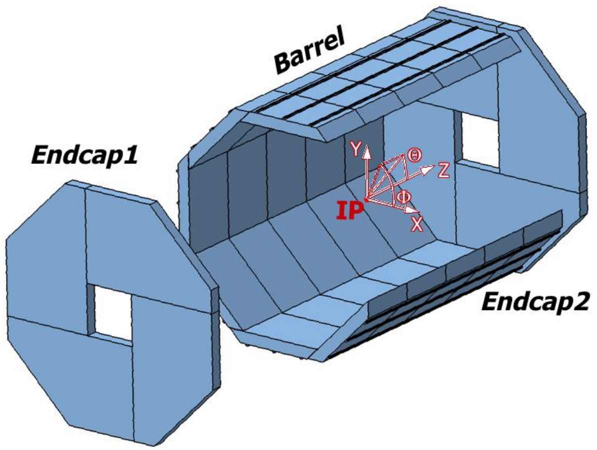
PFA-ECAL options at future lepton colliders

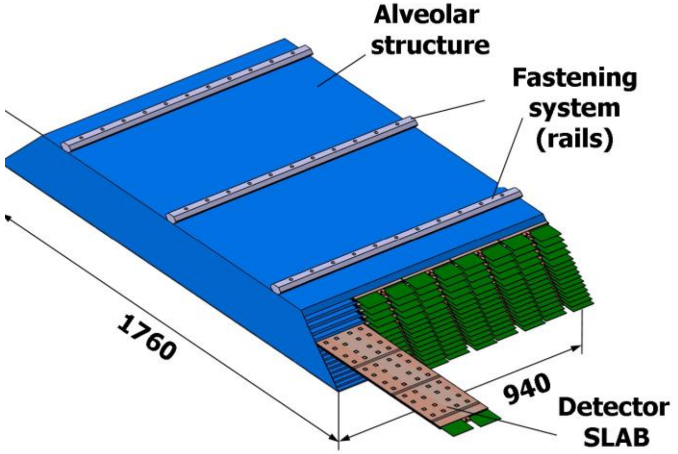
- Tungsten as absorber material
  - Narrow shower profiles
  - Compact design
  - Good separation of EM and hadronic showers
    - $X_0 = 3.5\text{mm}, R_M = 9.3\text{mm}, \lambda_I = 99.5\text{mm}$
- Active materials for detection
  - Silicon sensors
    - Compact layout, capable of pixelization, intrinsic stability
  - Scintillator + SiPMs
    - Mature technology, cost effective
- Both two options are being investigated in CALICE
  - Developments of technological prototypes

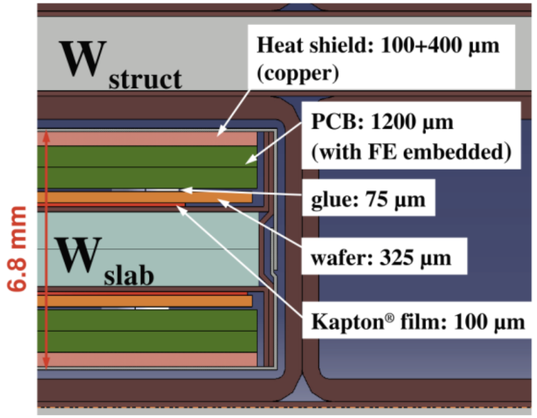




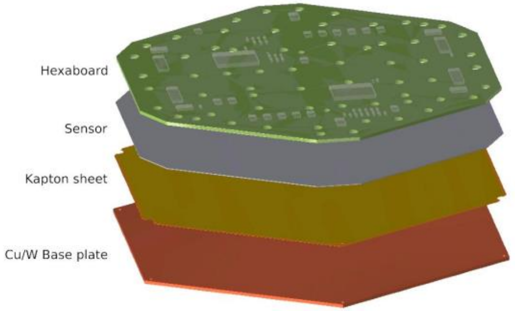
PFA-ECAL: Silicon-Tungsten option







Silicon Module for CMS-HGCAL



Silicon sensor (pixelized)

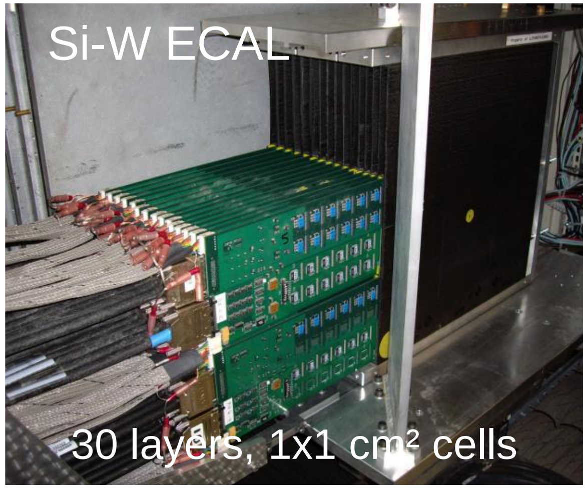
Chip-On-Board

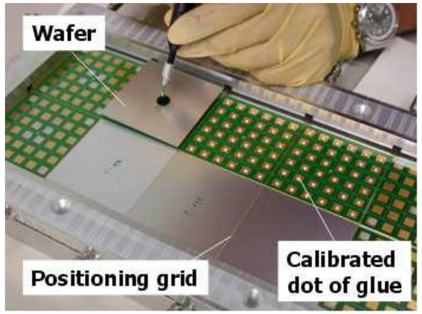
- Sensitive layers: stringent requirement on space
  - Silicon sensors: 0.32~1.0 mm thick
  - PCB + ASICs: 1.8 mm thick (challenging)
  - COB 1.2mm thick demonstrated: ASICs wire-bonded
- Technology application in the CMS-HGCAL project
  - Major focus on radiation hardness and active cooling (-35 degrees with dual-phase CO_2)
  - Challenges due to complicated geometry in endcap regions
  - Invited talk by David Barney in the same session: stay tuned

Overview: SiW ECAL prototype developments

Physics prototype

Proof of principle 2003 - 2011





No. channels: 9720

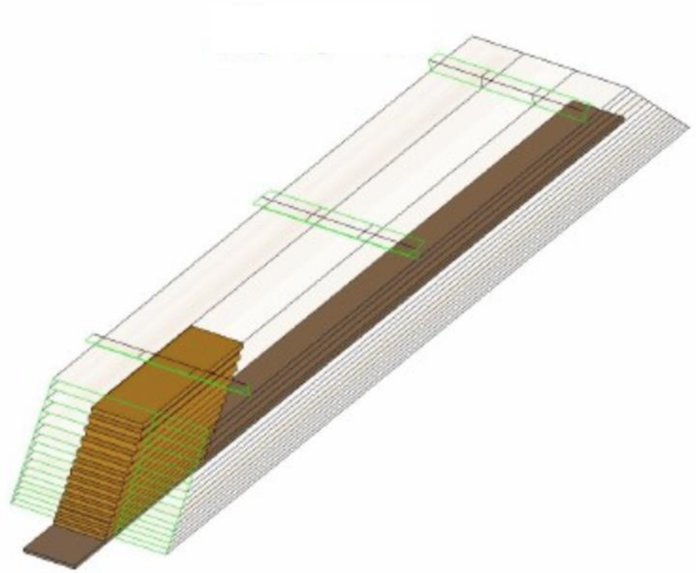
Pixel size: 1x1 cm2

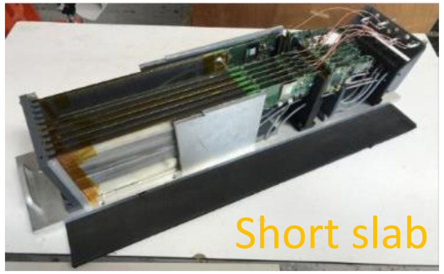
Effective $R_M = 1.5$ cm

Weight: 200 kg

Technological prototype

Addressing engineering challenges: since 2010





No. channels: 45k

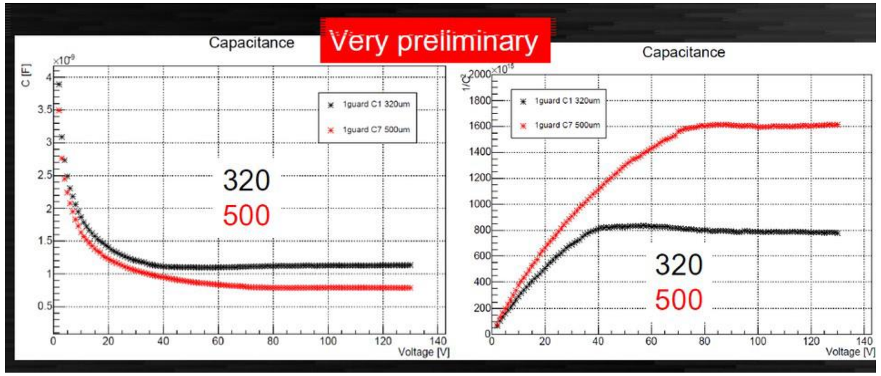
Pixel size: 0.55x0.55 cm2

Effective $R_M = 1.5$ cm

Weight: ~ 700 kg

Sensors: silicon wafers with PIN diodes

ILD design: **low cost, ~2000 m2**
Minimized number of manufacturing steps
Target: 2.5 EUR/cm2
Now : 10 EUR/cm2 (in Japan)

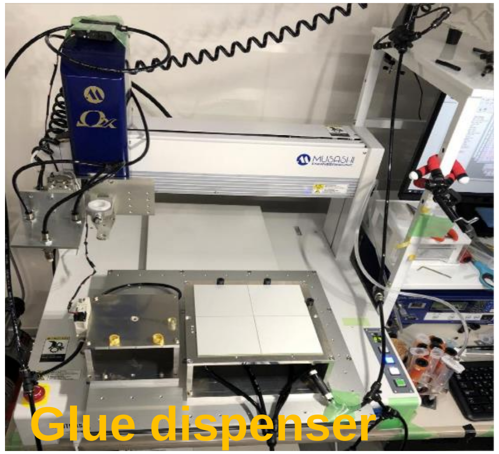


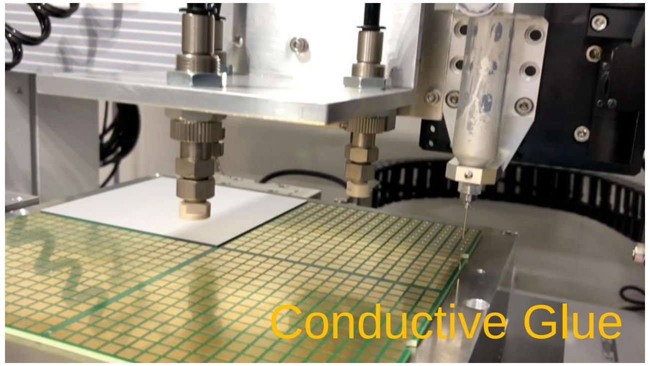
IV and CV characterizations

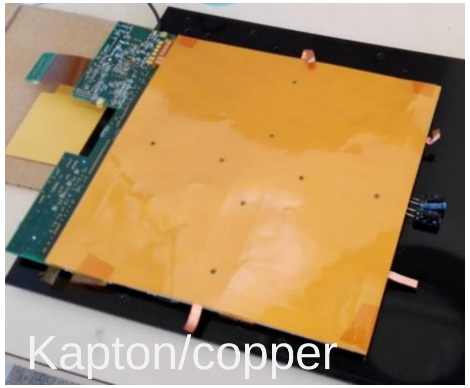
- Breakdown voltage >500V
- Current leakage <4 nA/pixel (DC coupled with chip)
- Full depletion at <100 V
  - ~40 V with 320 um, ~70 V with 500um

HPK Prototype

256 PIN diodes, 0.25 cm2/diode,
9 x 9 cm2 total area



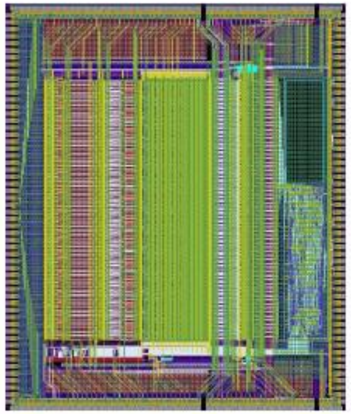


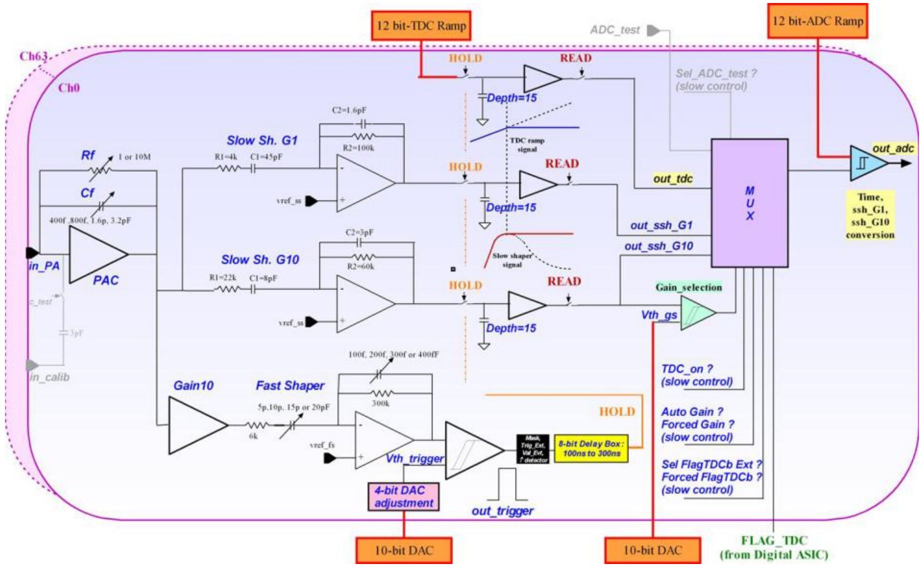


- Wafers are glued to PCB (robot at LPNHE & Kyushu U.)
  - Segmented guard-rings layout as an option
- Silicon sensor bias via a copper/Kapton sheet

Front-end electronics for silicon sensors

- SKIROC ASIC: full integrated electronics
  - 64 channels, SiGe 0.35µm AMS, Size 7.5 mm x 8.7 mm
  - Variable-gain charge amplifier
  - 12-bit Wilkinson ADC (also for TDC ramp)
  - Digital logic: acquisition, conversion, SCAs and I/O
  - Large dynamic range
    - High and low gain modes: 0.1~ 2500 MIPS
  - Auto-trigger at typically ~0.5 MIP
  - Low power: 25µW/ch featuring with power pulsing
- SKIROC ASIC: core ingredient in SiW ECAL prototypes
  - ECAL layout: evolution with PCB and chip packaging
- Note: SKIROC is not designed for circular colliders
  - The successor chip “HGCROC” developed for HL-LHC CMS-HGCAL project can be a better reference for continuous operation mode





S Callier et al 2011 JINST 6 C12040

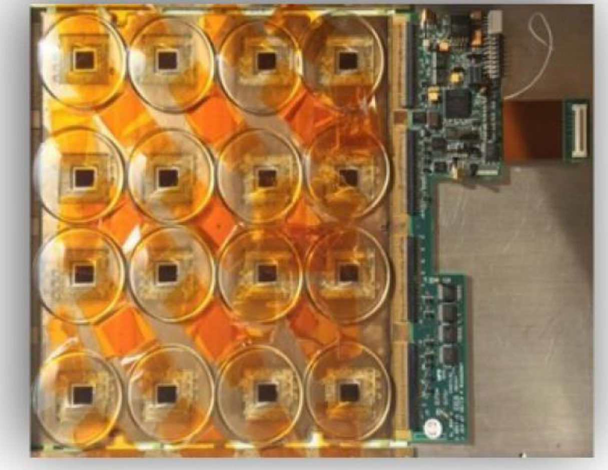
SiW-ECAL: towards system integration

- Very dense **PCBs *aka* FEV** with 1024 readout channels (with digital, analogue, clock signals) in a 18x18 cm board

FEV10-12

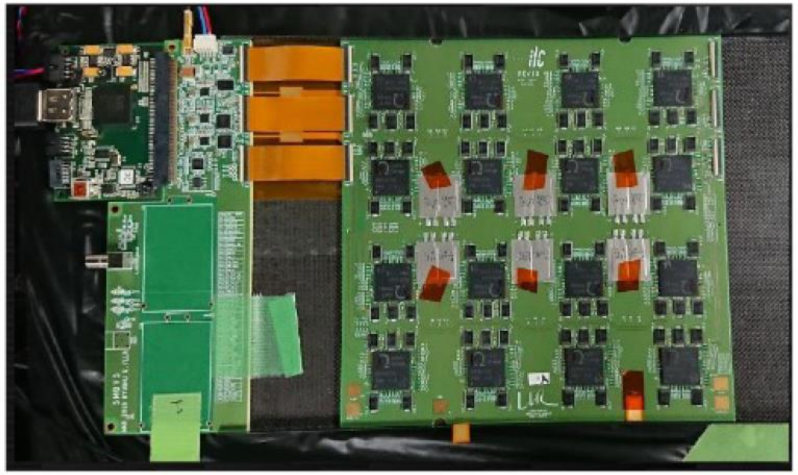
- ASICs in BGA Package
- Incremental modifications
  - From v10 -> v12
  - **Main "Working horses" since 2014**

FEV_COB



- ASICs wirebonded in cavities
- COB = Chip-On-Board
- Current version FEV11_COB
- Thinner than FEV with BGA
- External connectivity compatible with BGA based FEV10-12

FEV13

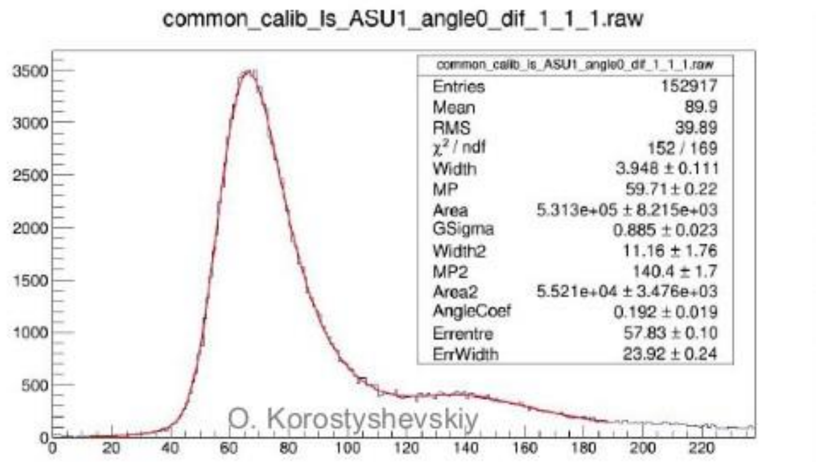


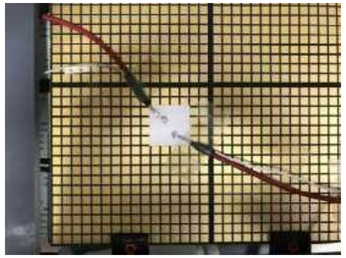
- Also based oin BGA packaging
- Different routing than FEV10-12
- Different external connectivity

Taken from A. Irles' talk at LCSW2021: "Status of the technological prototype of the CALICE SiW-ECAL"

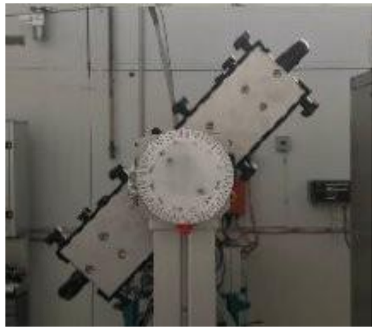
SiW-ECAL: long slab prototypes

- Daisy chain of 8 ASUs (extendable to 12)
  - Corresponding to typical barrel ECAL length
  - Based on FEV12 ASU (& SMBv4)
  - No ILC geometrical constraint (thickness)
  - Baby-wafer 4x4 pixels on each ASU
- Goals
  - To validate the electrical behavior of a long slab: clocks, data integrity, noise level on length

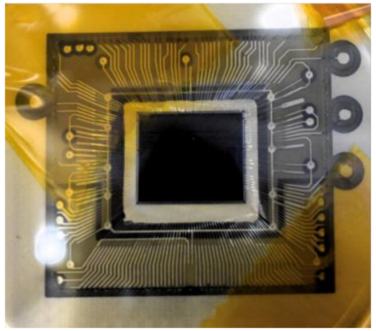


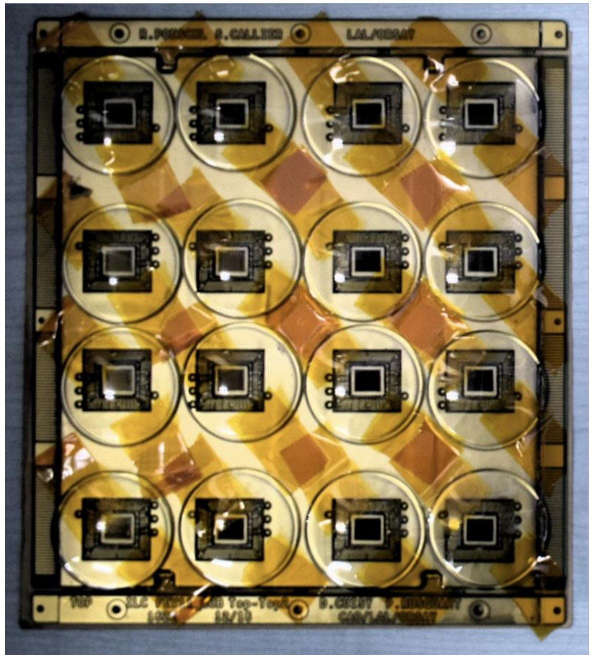


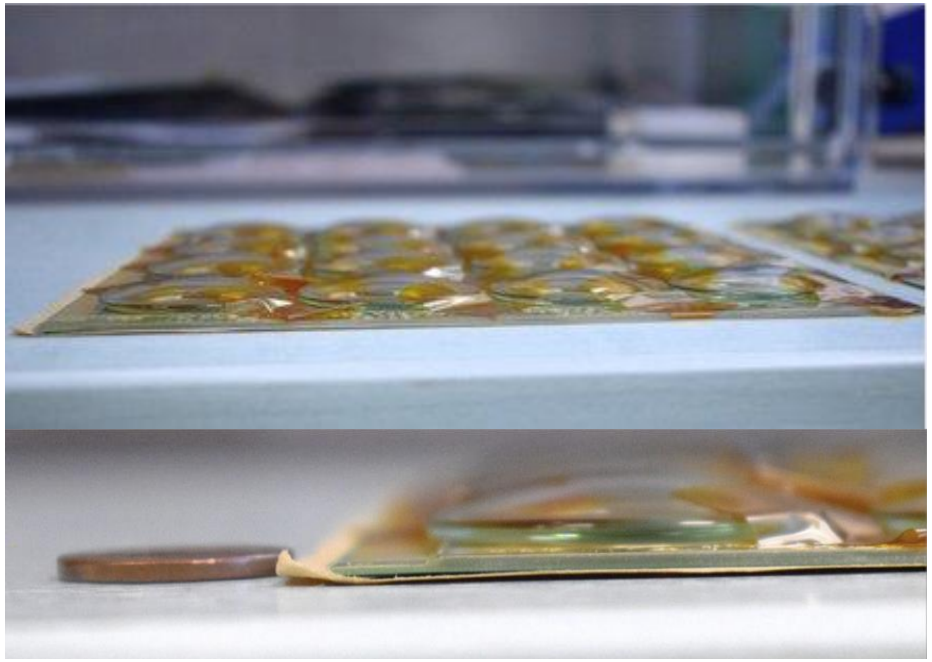
DESY beam tests in 2018



SiW-ECAL: address challenges from space constraints

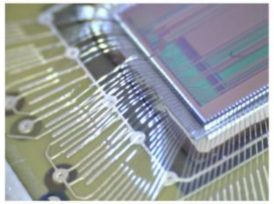




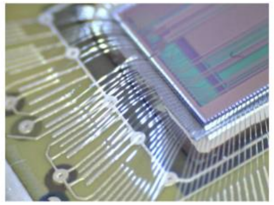


- Module assembly chain established
- Ultra thin PCB: Chip On Board (COB)
  - ILD constraints: total space for ASICs and PCB 1.8mm
    - Very thin board: 1.2mm 9-layer PCB, good planarity (issue for gluing)
  - PCBs with naked ASICs placed in carved cavities and wire-bonded
  - Investigating alternative options of encapsulating

Zoom into ASIC cavities



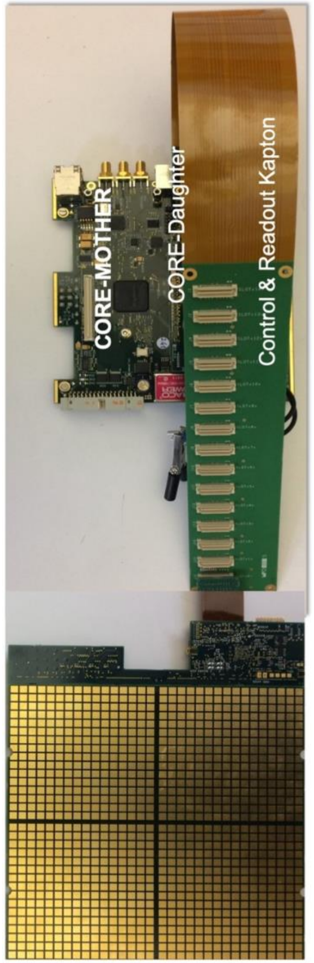
Before application of epoxy



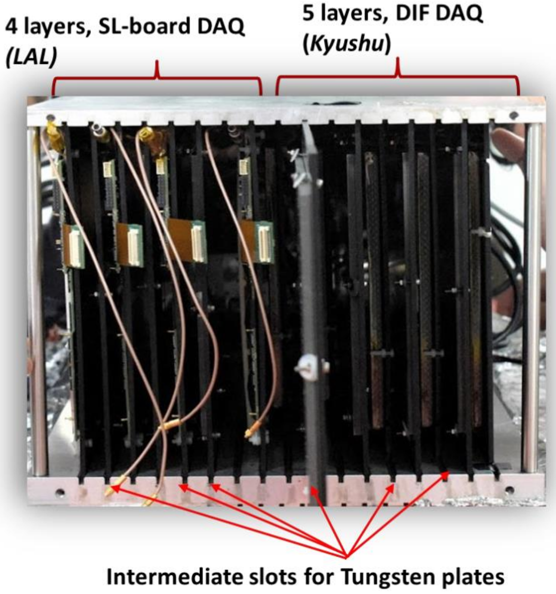
After application of epoxy

SiW ECA: ready for the 2021 test beam campaign

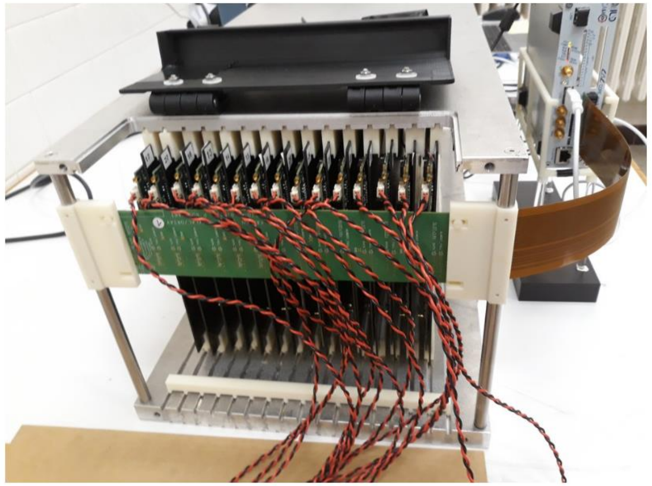
Test bench 2018



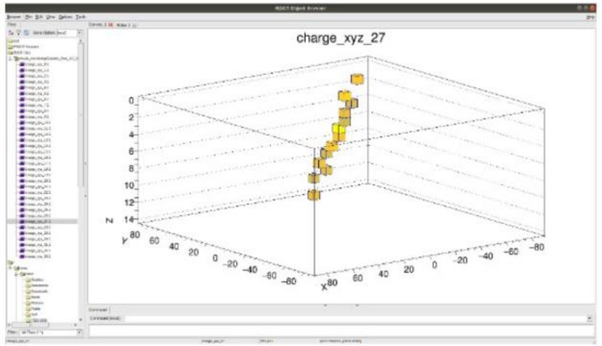
Beam test 4 layers in 2019



15 layers in 2020:
15000 cells in readout



First cosmic (Adrian Irles)



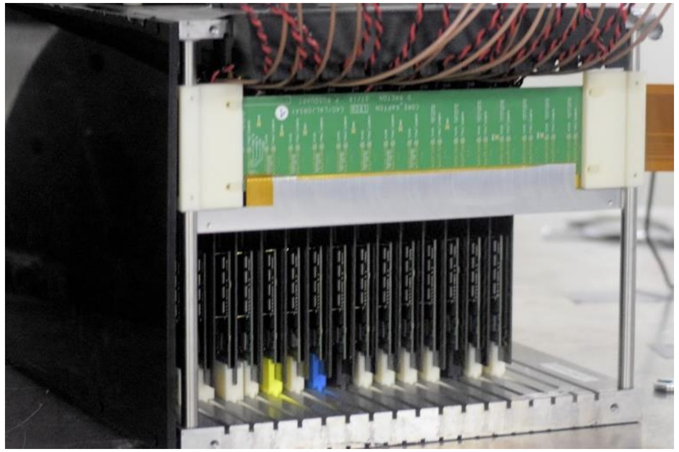
- Rapid development of compact readout electronics
- For the first time all components at hand that could be installed in a lepton-collider detector
- Beam test at DESY is ongoing: Nov. 1-15, 2021

Over 15 layers ready for beam test (FEV10, 11, 12, 13 and COB)

“Live” from the DESY Beam Test

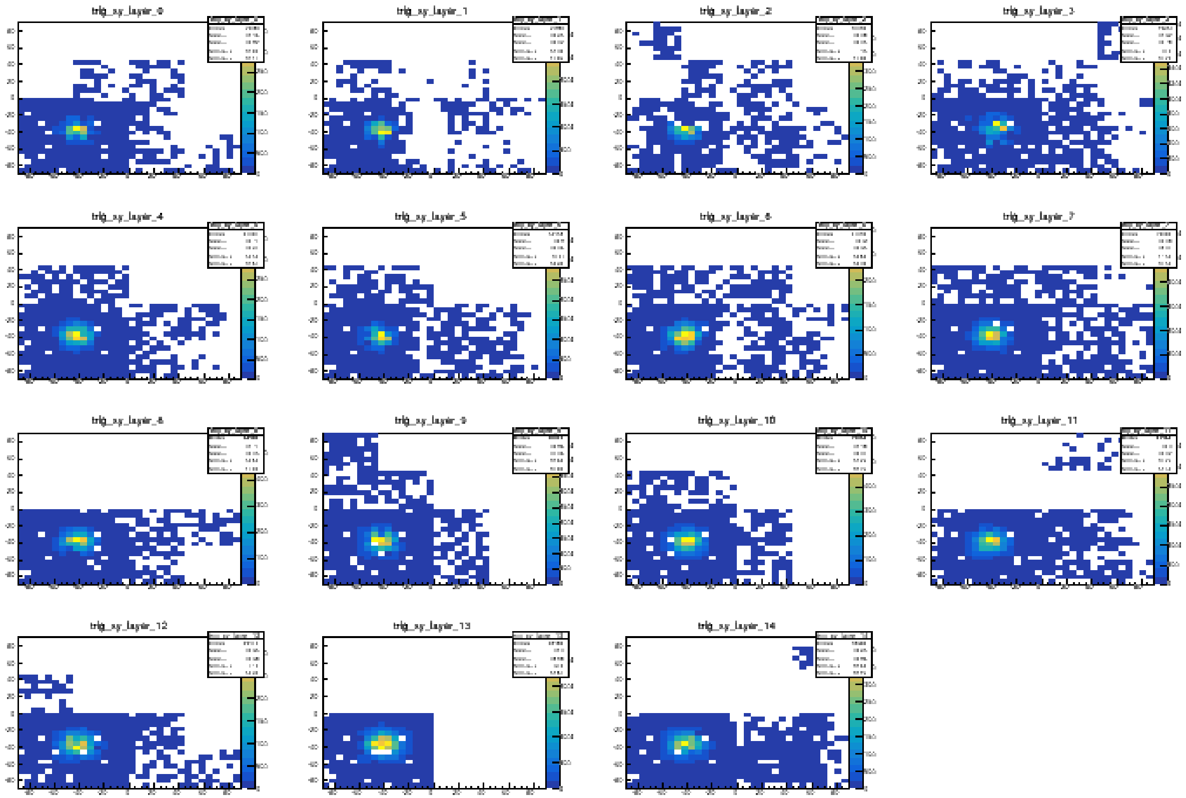
Fresh results (Nov. 8) from Roman Pöschl (IJCLab)

Detector Setup



Detector in beam position

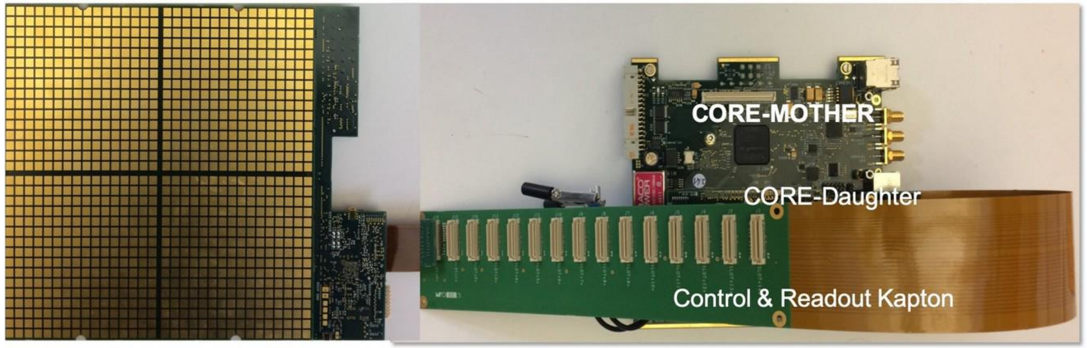
Hit maps of all 15 layers

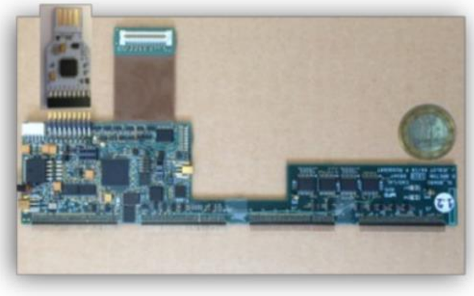


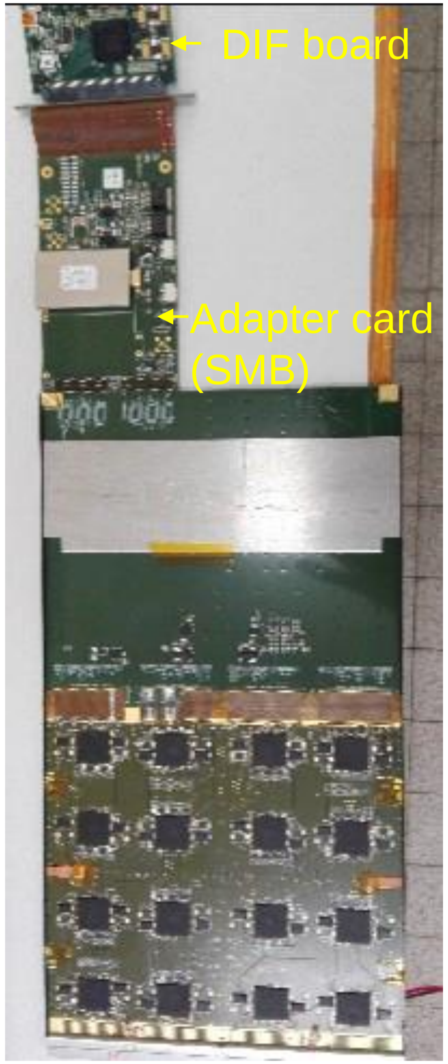
- DESY Beam Test 1/11/21 – 15/11/21
  - Successful operation of the prototype composed of 15 layers (15360 cells)
  - Smooth data taking as we speak
  - Exciting and important results can be expected

SiW-ECAL: ultra compact DAQ

- Core Mother-Daughter system
  - Able to control and read up to 30 SLboards
- SL-Board
  - The sole interface for the ~10k channels of a slab
- **The new DAQ fits tight space requirements**







Detector Interface

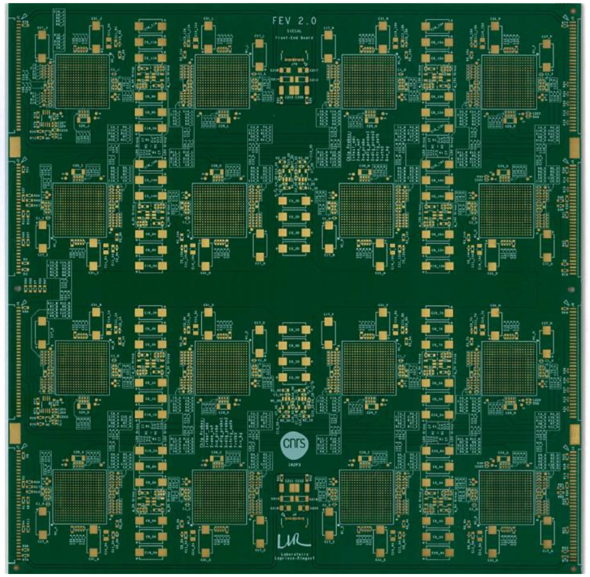
For signal buffering and power regulation

Before 2019

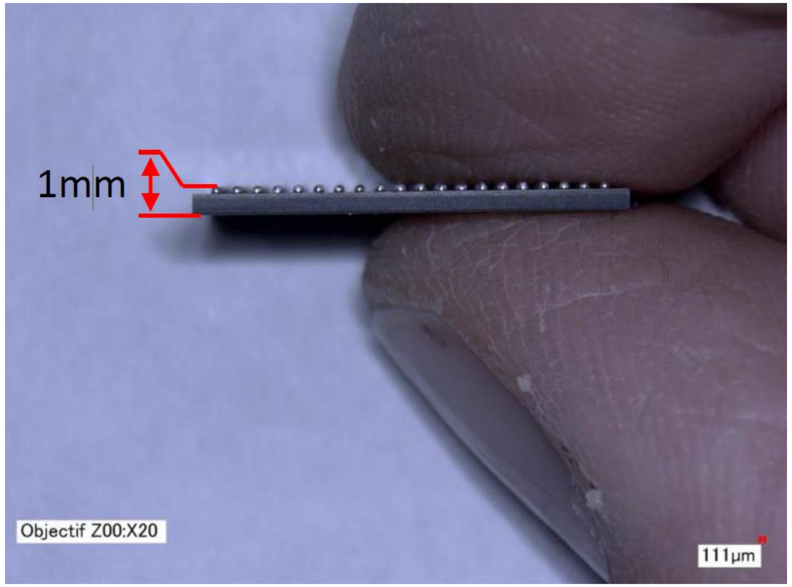
Since 2019

SiW-ECAL: new developments in front-end electronics

- Design new front-end board (FEV2.0)
  - Updates for LV power distribution, buffer for slow control
  - Change HV distribution for wafer: add HV filter per wafer, FEV drive HV instead of Kapton
  - New HV Kapton: 1 per FEV instead of 1 per slab
- New packager for SKIROC2A (NCAP in China)
  - 390 chips packaged, first results look good; will fully evaluate performance with test stand

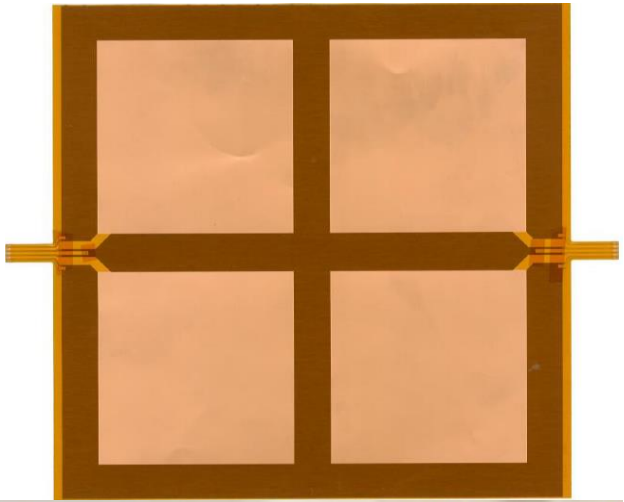


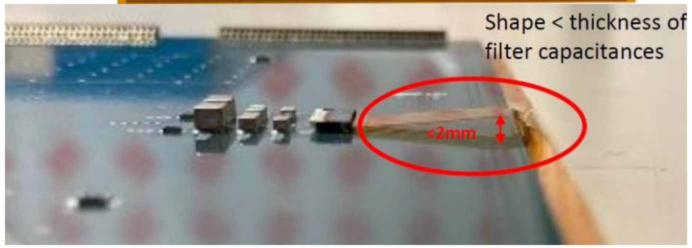
FEV2.0: 180x180mm



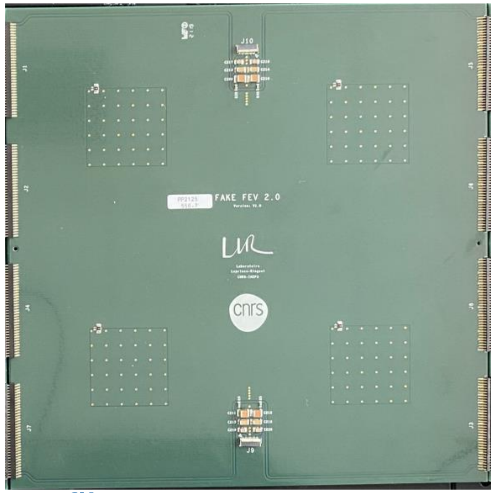
SiW-ECAL: new developments in front-end electronics

- New design of HV Kapton
  - New design: 1 Kapton per front end board -> easier to insert/replace in long slab
    - Better wafer protection (handling) HV propagate through FEV connector + filter to wafers
  - Old design: 1 Kapton for 10 boards (difficult and expensive solution)
    - Glue 40 wafers on single Kapton, incompatible with FEV interconnection connector

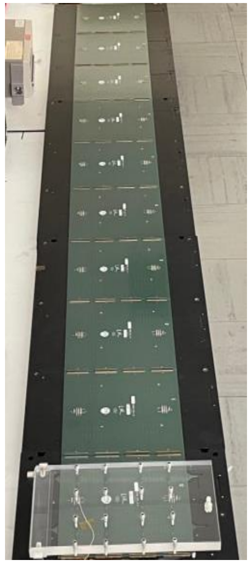




- “Fake” front-end board and long slab: leak current
  - Mockup to study HV distribution and mechanical assembly



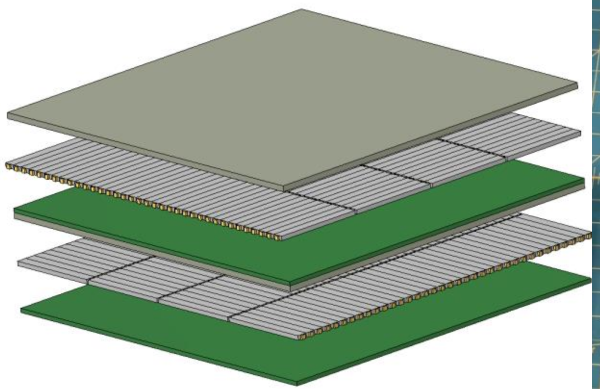
Only HV filter, connectors are mounted

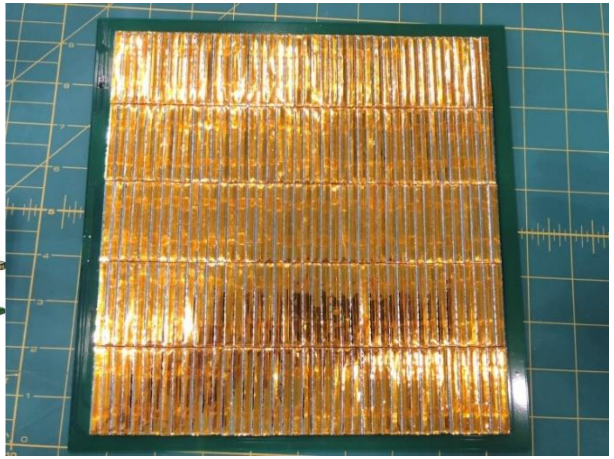


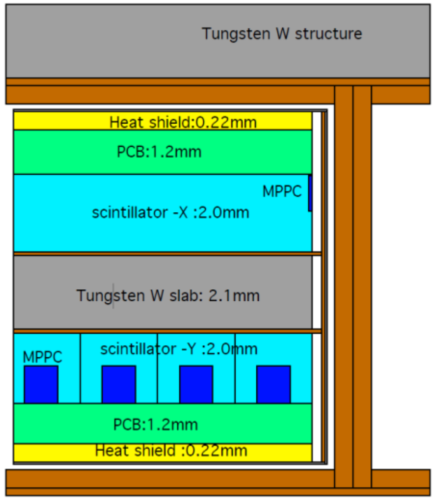
1.8 m long slab

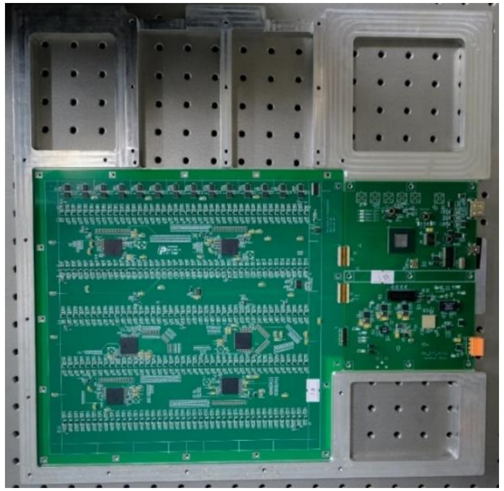
Connectors

PFA-ECAL: Scintillator-Tungsten option





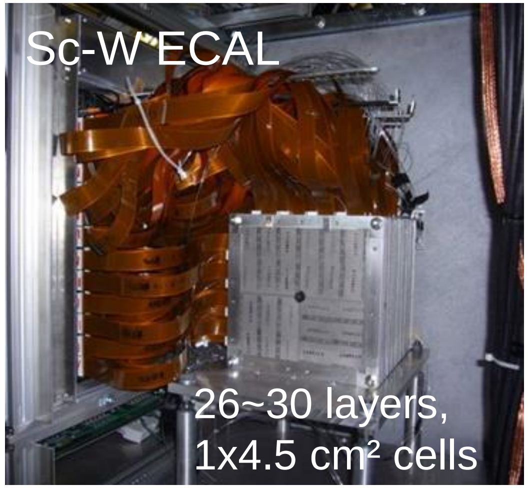


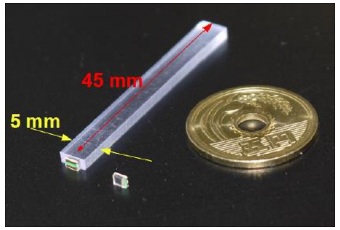


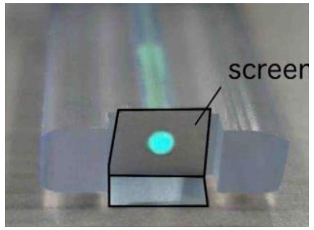
- Sensitive layers: challenges from space
  - Scintillator strips: 2mm thick
  - PCB + ASICs: considerably thicker than 1.2 mm in design specs (quite challenging)
- CEPC ScW ECAL prototype constructed
  - Over 6700 channels, 32 layers, air cooling
  - Commissioning with cosmic and beam particles
  - Close collaboration between Chinese and Japanese groups within CALICE

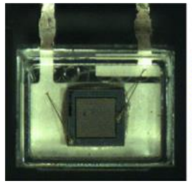
Overview: ScW ECAL prototype developments

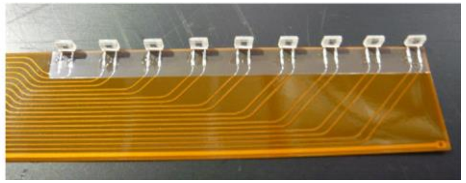
Physics prototype



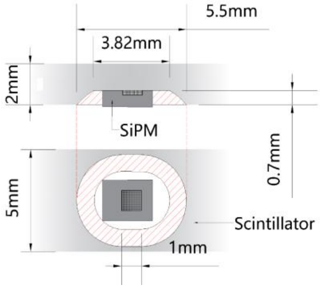








Technological prototype

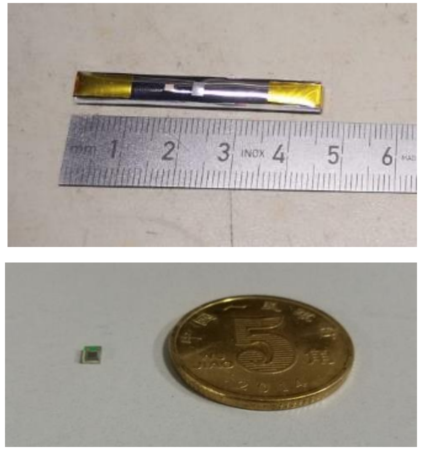


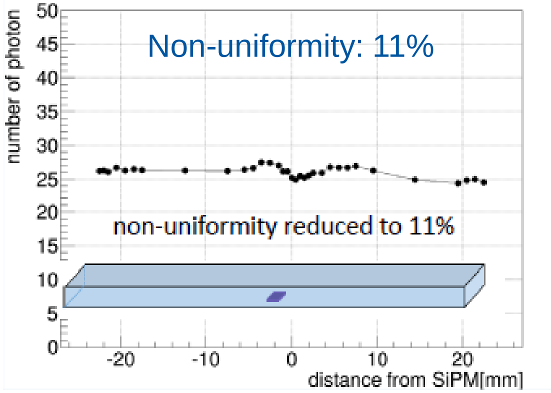
- Physics prototype
    - 30 layers with 2160 channels
    - Scintillator strip + WLS fiber + SiPM
    - Tested at DESY and FNAL with electrons during 2007 and 2009

- Technological prototype
    - 32 layers with ~6700 channels (SPIROC2 chips)
    - Scintillator strip directly coupled with SiPM
    - Tested at USTC and IHEP (BEPC-II E3 beam line) with cosmic muons and hadrons
    - Not able to perform DESY beam tests due to Covid

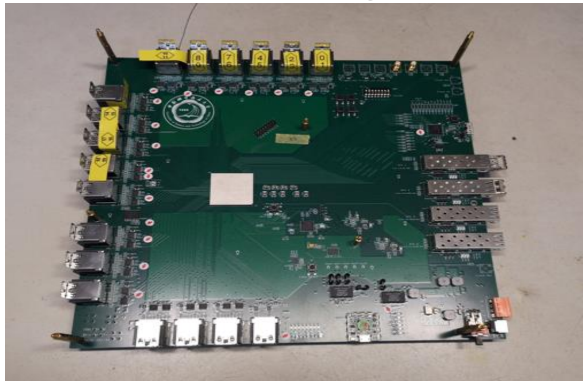
ScW ECAL prototype construction: reminder

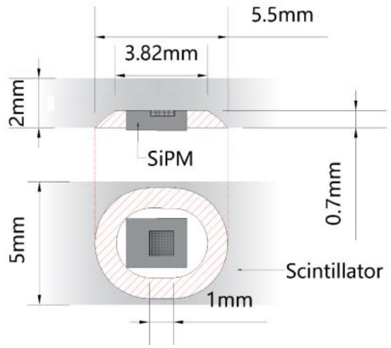
- Scintillator strip: directly coupled with SMD-SiPM
  - Response uniformity scan along strip length direction
- Multiple ECAL readout boards: commissioning tests with DAQ





FELIX-based DAQ board



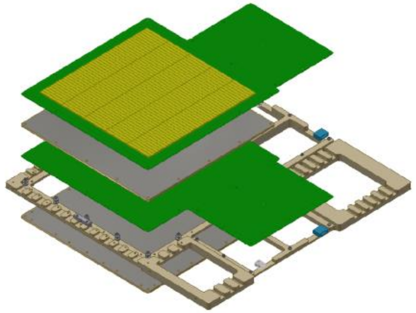


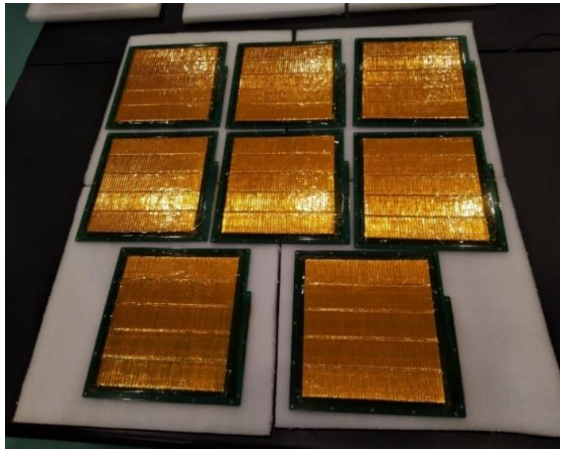
SPIROC2E chip on EBU

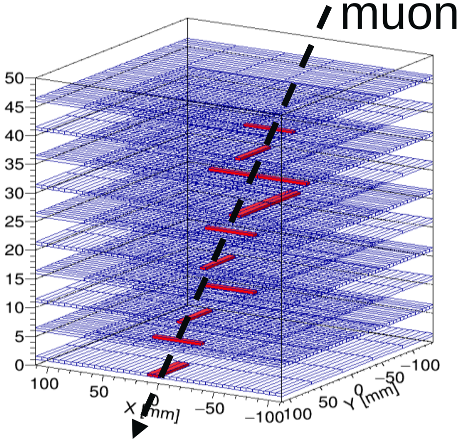
Multi-layer boards: ageing tests in a cabinet

ScW ECAL prototype construction: reminder

- Scintillator strips: individually wrapped, QA/QC (visual and dimension check)
- Prototype with 16 “super-layers”
  - Each “super-layer”: 2 sensitive layers and 2 CuW plates fixed onto one frame



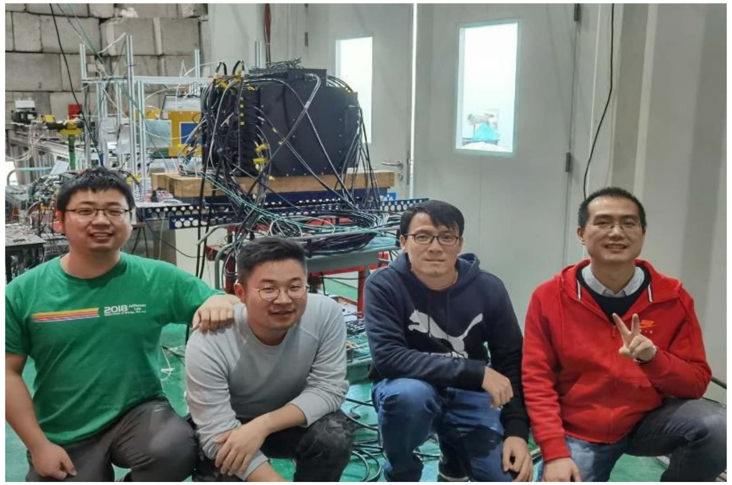


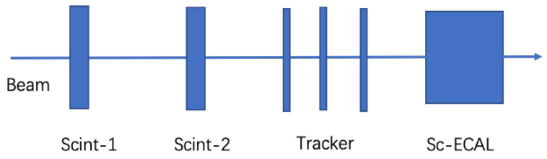


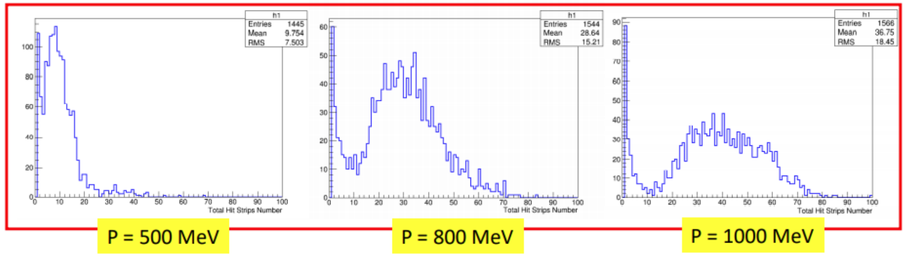
ScW ECAL prototype: first beam test at IHEP

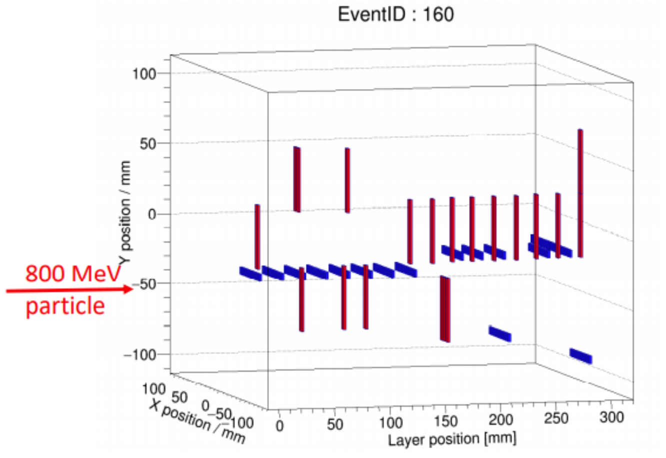
- BEPC-II E3 beam line at IHEP campus
  - Secondary particle beam
- Mixed particles with protons and pions
  - Protons dominated
  - Momentum : 300MeV-1.2GeV
  - Low event rate: less than 100 per minute
- Rehearsal for future beam tests at DESY/CERN
  - Successful assembly and data taking (12k events)

ScW ECAL team (part) during beam test 2020

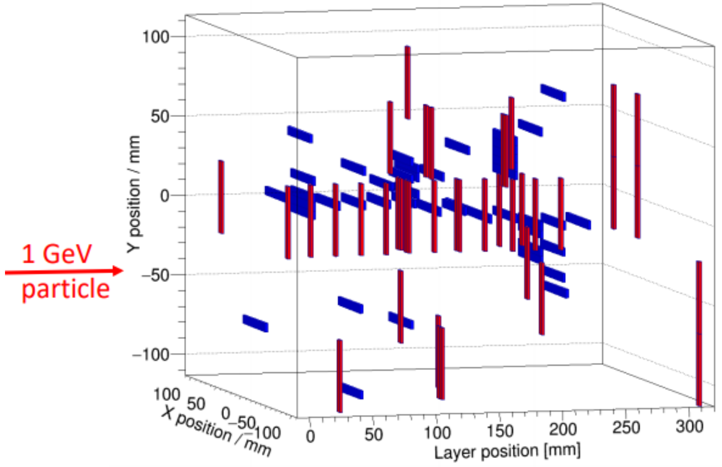






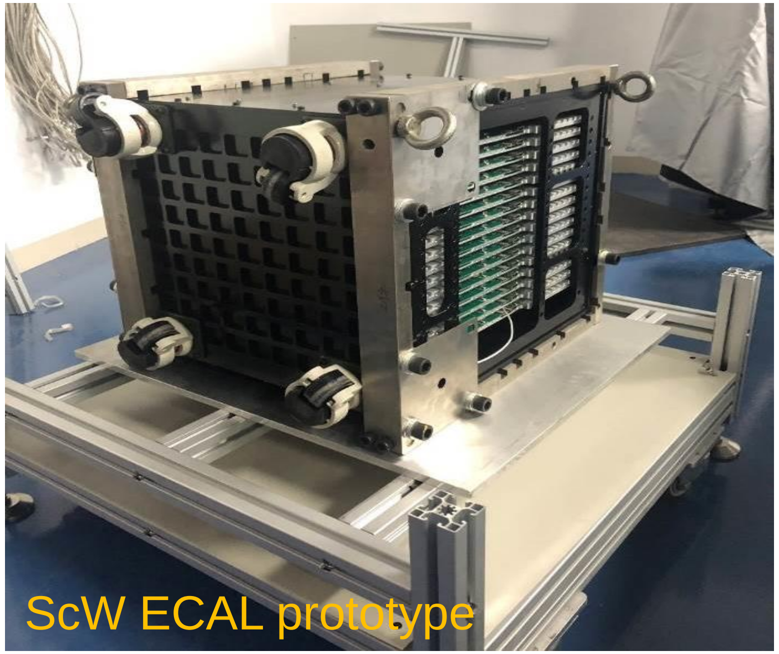


1GeV proton candidate

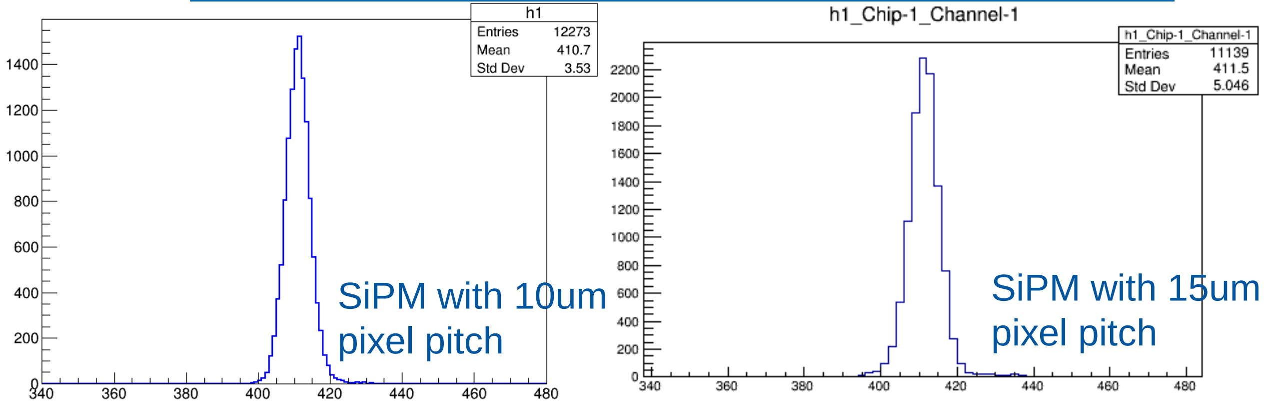


ScW ECAL prototype: commissioning with cosmics

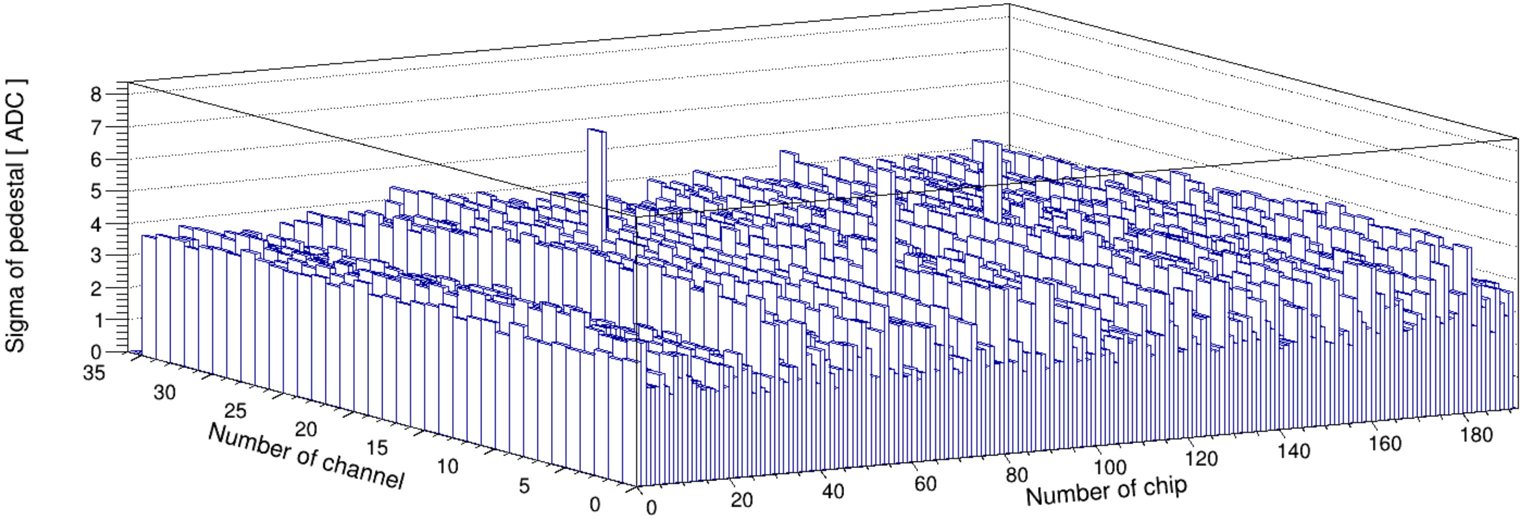
- Long-term tests with cosmic muons
  - Pedestals, SiPM noises



Pedestals of one channel: 10um vs 15um SiPMs

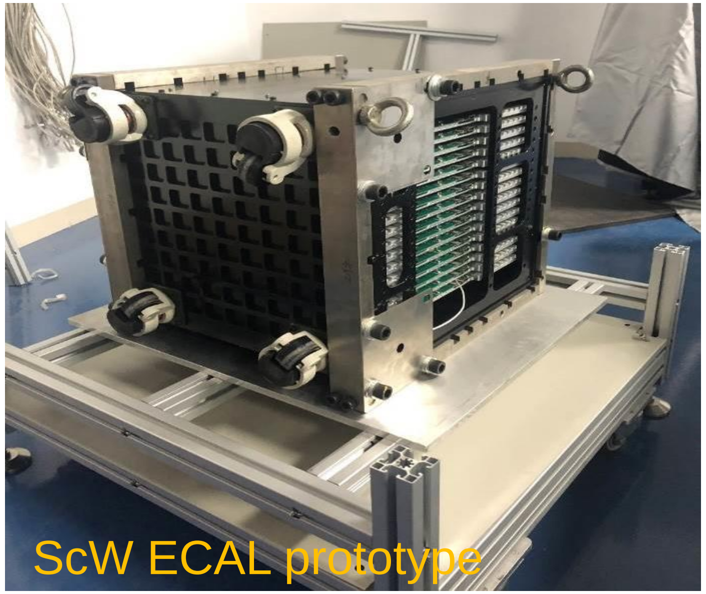


Pedestal width of all channels

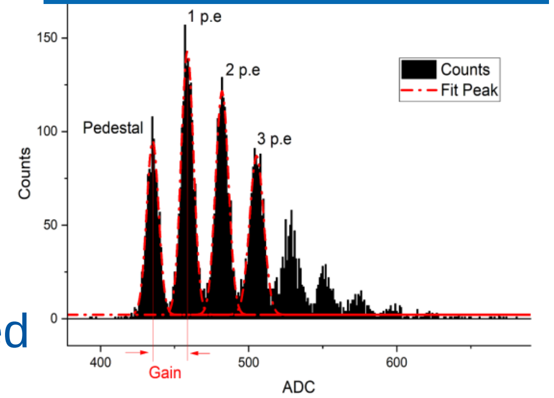


ScW ECAL prototype: commissioning with cosmics

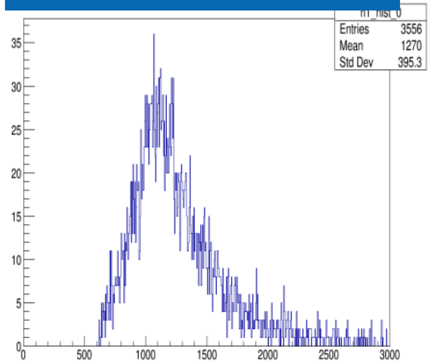
- Long-term tests with cosmic muons
  - Pedestals, SiPM noises
  - Calibration with all SiPMs
    - SiPM gain: single photon spectrum
  - MIP response
- Tracking performance extracted with cosmics
  - Better than 2mm positioning resolution achieved



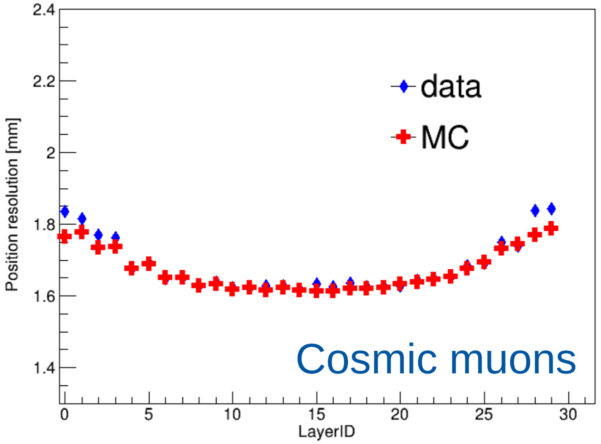
Single Photon Spectrum in SiPM with LED



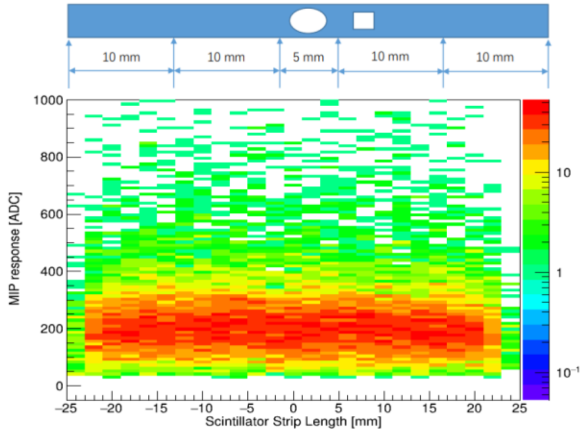
MIP response with 15um- SiPM



Tracking precision in each layer

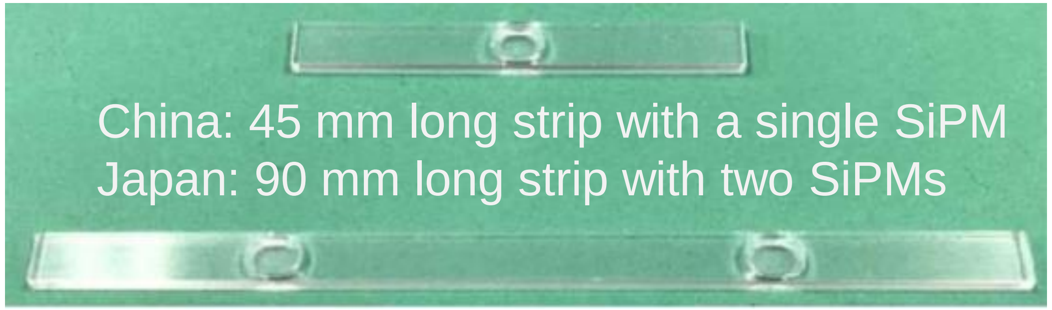


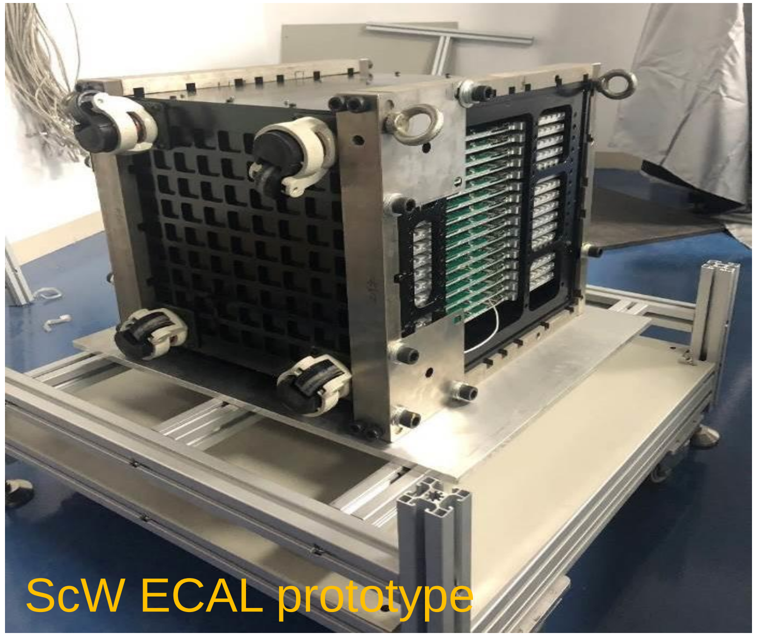
Response uniformity with muons



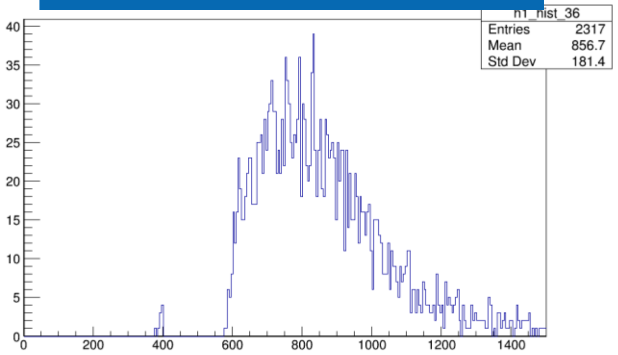
ScW ECAL prototype: commissioning with cosmics

- Long-term tests with cosmic muons
  - MIP response and temperature impacts
- Scintillator strip: two different designs
  - Chinese group: 45mm strip (equipped 30 ECAL layers)
  - Japanese group: 90mm long strip (equipped 2 layers)
    - Coupled with two SiPMs (15um pixel pitch)

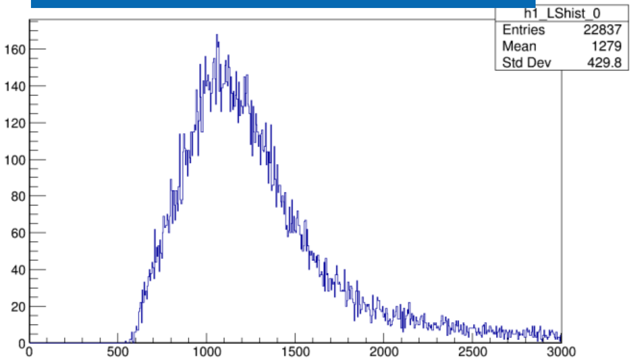




MIP response of one single SiPM



MIP response of two SiPMs combined

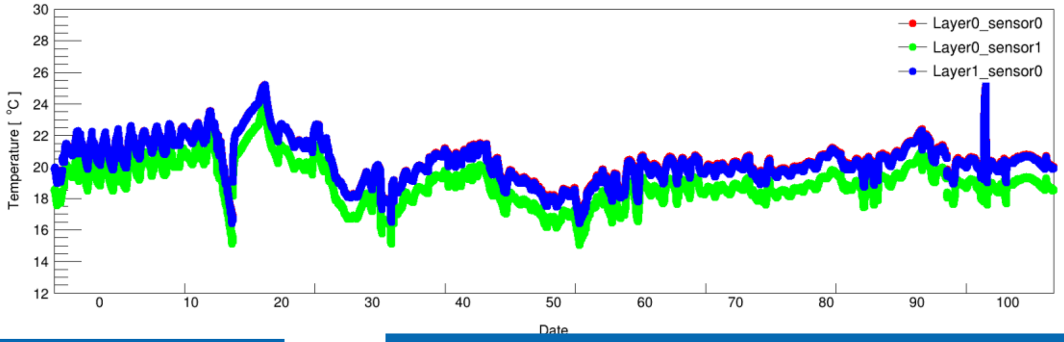


Higher S/N ratio achieved; can use lower trigger threshold

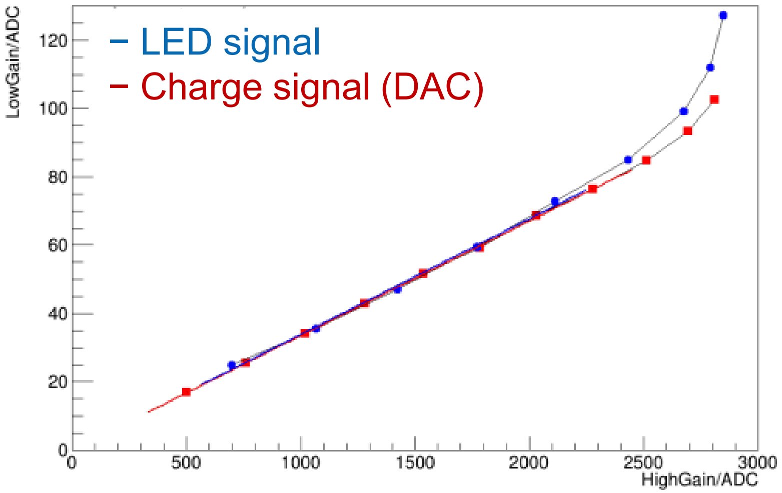
ScW ECAL prototype: commissioning with cosmics

- Long-term tests with cosmic muons
  - Calibration with all ASICs (SPIROC2E)
    - High gain vs low gain: inter-calibration
    - With LED, charge injection and cosmics
  - MIP response and temperature impacts

Long-term temperature monitoring

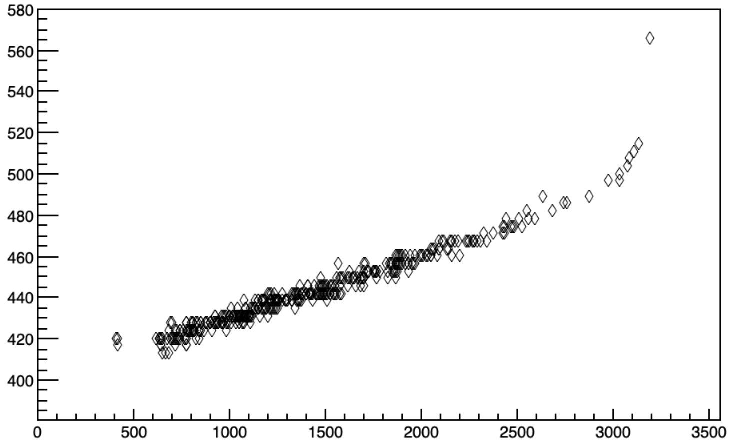


ASIC HG/LG inter-calibration



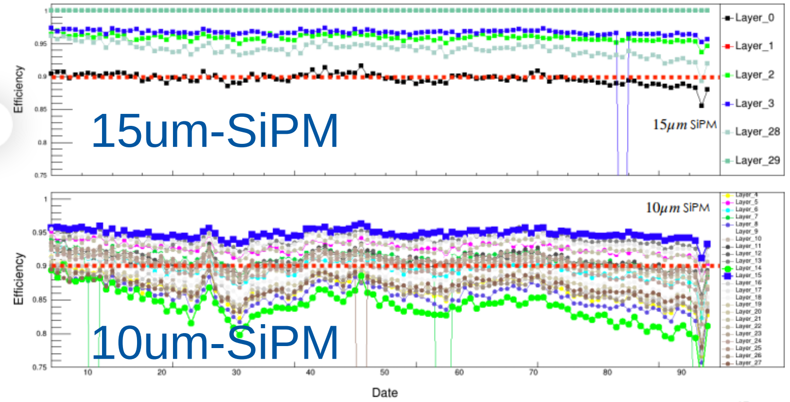
Consistent results: HG/LG ratio with LED is 29.5, and DAC is 29.8,

ASIC HG/LG studies with cosmics



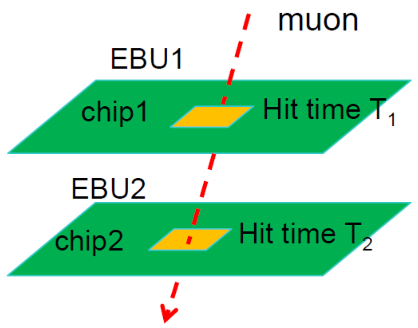
Data with cosmic rays show similar HG/LG curve: ongoing studies

Detection efficiency

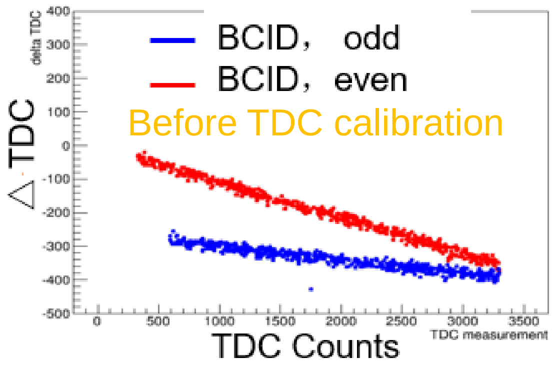


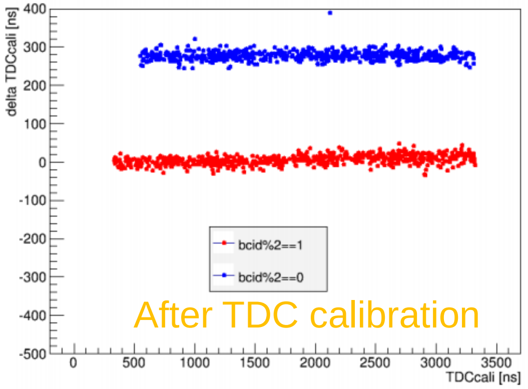
Detection efficiency is generally stable; but also observed that it gradually dropped for 10-um SiPMs

ScW ECAL prototype: time measurements

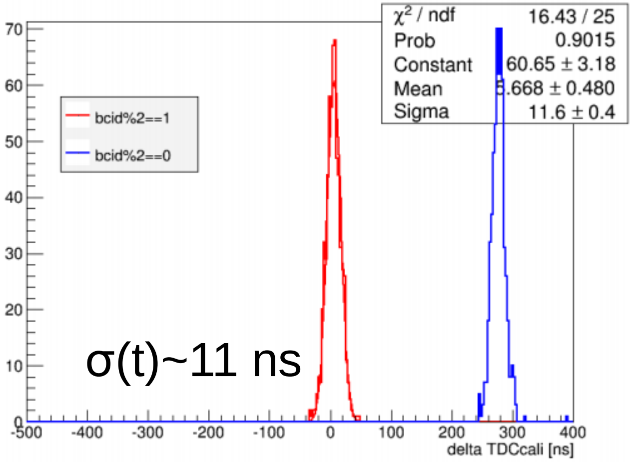


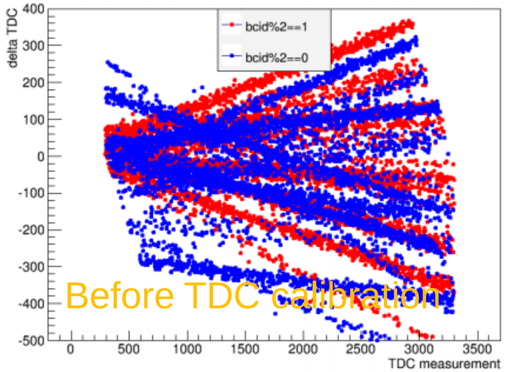
- Data of cosmic muons: timing performance
  - Based on the time calibration with pulse generator: TDC tics -> ns
    - to calibrate the “TDC offset” per chip and per channel
  - TDC differences of channels measured by the two chips

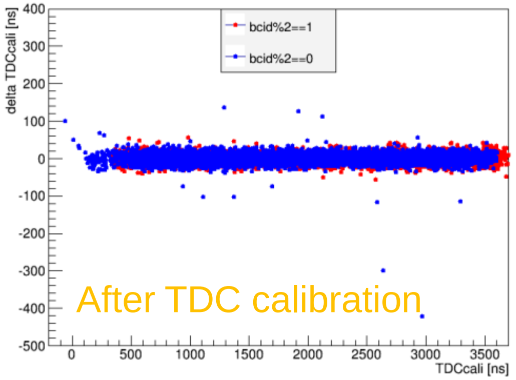




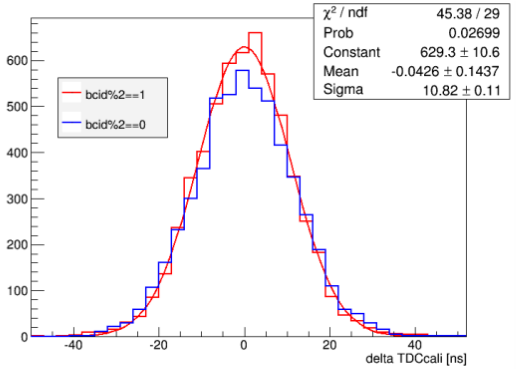
Two chips on two EBUs







All chips on the two EBUs



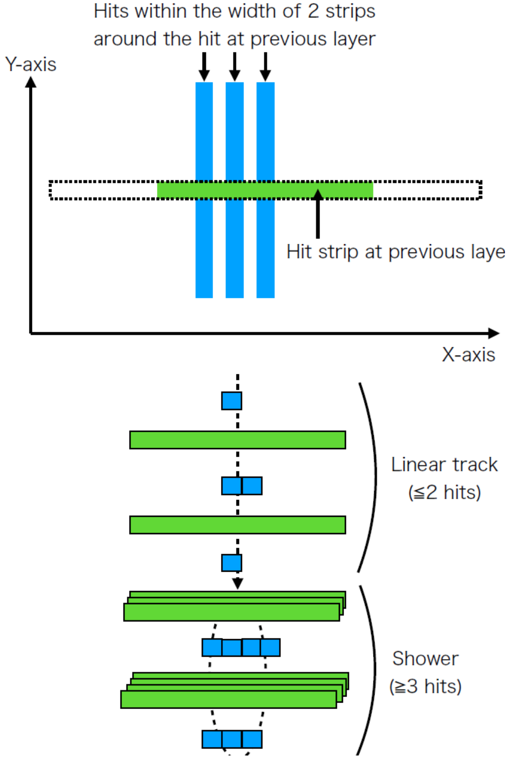
Time resolution ~10.8 ns

ScW ECAL prototype: shower studies using cosmic-rays

- Development of shower finding algorithm
- Further exploit the cosmic data, comparison with simulation

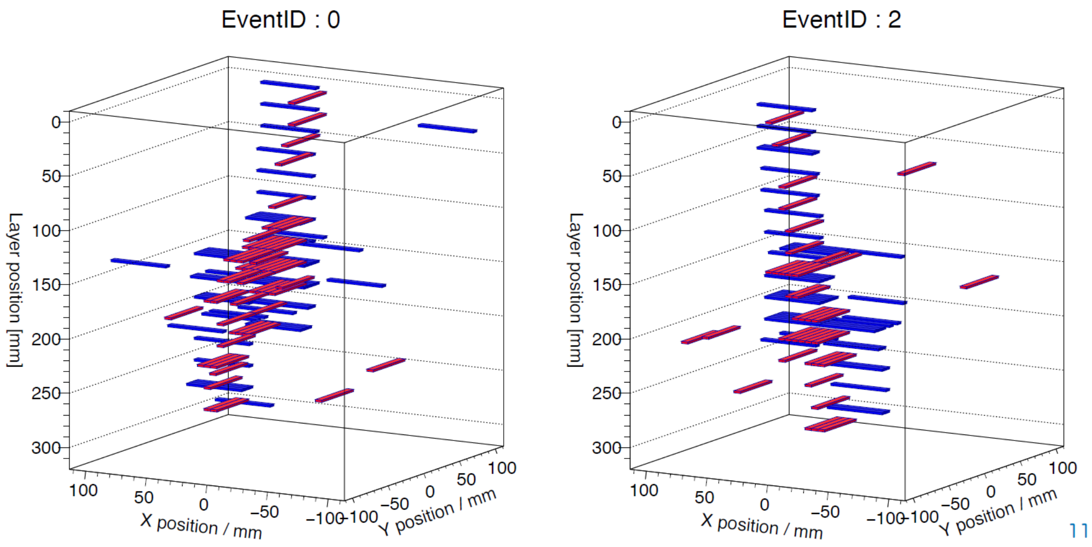
Shower study using cosmic-ray

- Shower search in cosmic-ray events
  - Possibility of performance study using cosmic-ray shower events is being considered
  - Comparison with simulation
- Shower finding algorithm
  - Get the hit position at previous layer
  - Search the hits at focused layer
    - Count the hits within the width of 2 strips around the hit at previous layer
    - ≤2 hits is just a particle track
    - ≥3 hits may cause the shower
  - Search the events which consist of linear track and shower
    - Search the ≥3 hits at the continuous 3 layers after the linear region



Results

- Some shower-like events can be obtained
  - 630 shower events in 1.75 * 10^6 cosmic-ray events
- Fully contained shower events are not included due to coincidence trigger with top and bottom layers

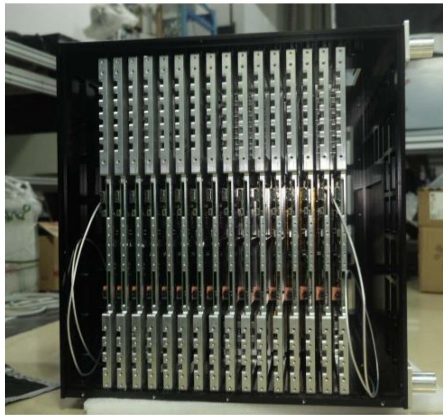


11

Naoki Tsuji's talk at CALICE Meeting Sep. 2021

Summary:

- Steady progress made on PFA ECAL prototypes within CALICE
- SiW ECAL option
  - Address challenges from technical requirements
  - Ultra Compact DAQ
  - In parallel to the workshop, testing a SiW ECAL prototype with 15k-channels (combined tests with other CALICE calorimeters foreseen for 2022)
  - Intense R&D activities ongoing
    - Ultra thin PCB, optimization of powering/HV in a long slab
    - Long slab: from an electronics prototype to a technological prototype
- ScW ECAL option
  - Successfully constructed a technological prototype with 32 layers (6700 channels)
  - Commissioning with long-term cosmic ray tests: demonstrate good performance
  - A first beam test was successfully done at BEPC-II E3-line in IHEP campus
  - Ready for beam tests at DESY/CERN in 2022/23 (with other CALICE prototypes)



Thank you!

References and collaborating institutions

- SiW ECAL

1. Adrian Irles, “Status of the technological prototype of the CALICE SiW-ECAL”, LCWS2021, Mar. 15-18, 2021
2. Fabricio Jiménez Morales, “Status of the technological prototype of the CALICE highly granular SiW-ECAL”, ILCX2021, Oct. 26-29, 2021
3. Jérôme Nanni, “A new (Very) Front End Board for the ILD SiW ECAL”, ILCX2021, Oct. 26-29, 2021

- ScW ECAL

1. Yazhou Niu, “PFA ScECAL prototype update”, CEPC Day, Jan. 22, 2021
2. Yunlong Zhang, “SciW ECAL Status for CEPC”, CEPC Day, Jul. 28, 2021
3. Yunlong Zhang, “Cosmic ray test of the SciW ECAL Technological Prototype”, CALICE Collaboration Meeting, Sep. 8-10, 2021
4. Naoki Tsuji, “LED-based calibration for ScW-ECAL prototype”, CALICE Collaboration Meeting, Sep. 8-10, 2021

Ongoing studies: scintillator-SiPM response

- Scintillator-SiPM stability: long-term monitoring
- Groups in China and Japan both observed drops of scintillator-SiPM response
  - Shinshu University: setup with a Sr-90 source
  - USTC: setup with LED and scintillator test bench